Laminated Electroformed Shape Memory Composite for Deployable Light-weight Optics

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Abstract- **Advances in earth and space instrumentation will come from future optical systems that can provide large, collecting areas of low areal mass density (< 10 kg/sq meter) at a cost much lower than current practice. Launch cost and volume constraints require mass and volume both be reduced to permit affordable systems using large apertures. Composite optics show promise for light-weight, stiff optical substrates, but surface finish has not been adequate for many applications. Electroplated, replicated optical surfaces of nickel have been used for producing smooth, accurate optical surfaces primarily for X-ray optics, but require high mass to be self-supporting. Combining a light-weight and stiff composite substrate with a high quality replicated metal optical surface combines the best properties of these disparate materials. Recent developments in polymer chemistry have led to development of resins that can be formed into structures with shape memory properties. The unique properties of shape memory resins in the composite provide a larger range of design parameters for production of usable optics, allowing repeated deployability and accurate recovery to replicated shapes, selective shaping of optical surfaces, and management of interface stresses. Results are presented from optical and structural tests of various mirror constructions that show progress towards a laminated, deployable optic. Key issues for successful space applications are interface stress control of the disparate materials, strain recovery of the resins for accurate deployment, and stability over the operating conditions of temperature and moisture loss. Initial requirements analysis and material properties measurements for both system and individual material target performance are presented with current status and goals for future development.**

I. INTRODUCTION

There is a need for larger collecting area to meet the goals of higher spatial resolution, better signal to noise, and more frequent revisit times possible from higher orbits. These all require larger apertures, in many cases larger than can be packaged into existing launch vehicle fairings. Mass and production costs per unit area must also be reduced to maintain systems affordability. Replication processes can produce the required optical surfaces while reducing the cost and manufacturing time for large area optics.

A. Application to Earth Observing Missions.

Earth observing missions urgently need to reduce payload mass and mission cost, while at the same time increasing spectral and temporal resolution. Light-weight deployable composite mirrors are ideally suited to these requirements. Missions previously limited to LEO can now afford the mass and cost of larger apertures needed at higher orbits to take advantage of greater observing time, thermal stability, and lower gravity disturbances. Examples include:

Microwave reflectors: Soil moisture and precipitation monitors require apertures in the range of 4 meters or larger to obtain adequate spatial resolution.

LIDAR and Space Communications: NASA is studying the feasibility of inexpensive, easily made, light-weight meter-class telescopes for space communication receivers, and atmospheric sensing LIDAR satellites for earth observing applications.

Space Telescopes: Ultra-lightweight composite mirrors are suited to the new generation of space missions requiring larger collecting apertures.

II. STRUCTURAL CONCEPT

Rapid advancement in materials technology has produced the capability for adding shape memory properties to the cyanate ester based polymers used for conventional fiber reinforced composite structures. This investigation combines a substrate of reinforced shape memory composite materials with a thin (~0.020mm) nickel layer. The lamination provides a high stiffness composite substrate for surface shape control and pointing agility, while the thin nickel optical surface provides a flexible, durable, low scatter and low stress optical surface.

Reflectors may be fabricated, heated, rolled, and "frozen" in a compact configuration to stow the optic for launch as in Fig. 1. The mirror is deployed by reheating in orbit, releasing the memory shape locked in the composite when it was initially cured on the replication mandrel.

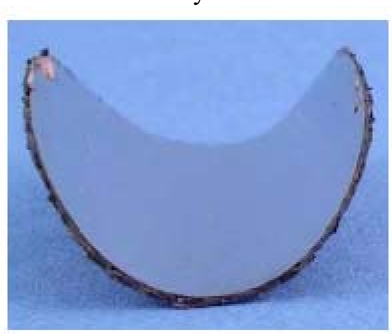

Fig. 1. A composite mirror of shape memory composite holds a stowed shape until deployment in orbit.

The composite structure of the mirror substrate simplifies integration of the optic into bench structures for improved athermalized performance and reduced instrument mass and complexity.

III. Replication technology

Space-based optical instruments have been increasing in size to gain corresponding increases in performance necessary to meet performance goals. Accurate deployment of large optical surfaces is required to fit larger apertures within a limited fairing volume. Composite replica mirrors are a relatively new class of super ligh-tweight optical mirrors with areal density in the range of 1-5 kg/m^2. They are fabricated by replication from a polished mandrel, using multiple layers or plies of fiber-reinforced polymer composite materials. The layup of composite materials on a single polished mandrel provides the opportunity for manufacture of multiple optics from a single, optically figured master. Large apertures may be assembled from multiple, easy to manufacture mirror segments. Requirements for these reflectors include surface figure accuracy and stability, surface smoothness, minimal thermal expansion and distortion, stiffness, strength and durability, low areal density, and resistance to atomic oxygen and solar radiation [1]. High accuracy replicated optical surfaces on graphite reinforced composites has been demonstrated and is reported in [2].

Replication processes provide optical designers with alternate choices for telescope mirrors that are lighter, cheaper, and faster to produce than conventional metal and glass mirrors, and easily made in multiple identical units [3]. Composite Mirror Applications, Inc. (CMA) has recently demonstrated a 0.6-m diameter composite replica mirror with an areal density of 2 kg/m^2, which is 1/3 to 1/10 that of other “light-weight” mirror technologies. A 2-m composite replica mirror recently fabricated by Composite Optics, Inc. for the European Space Agency’s Herschel Space Observatory (formerly called FIRST) demonstrated that duplicate composite mirror facesheet segments could be replicated off a single small mold, reducing mission costs by eliminating the time-consuming and costly polishing of a large mirror surface. An areal mass of 10 kg/m^2 was achieved in this prototype demonstration part, which met all optical performance requirements for the infrared telescope system. Deployable composite replica optics have also been manufactured, by making them thin and flexible enough to roll up, with deployment consisting of releasing them to spring back to their original shape [4].

IV. New materials in the equation

Recently developed shape memory polymer (SMP) materials maintain the high modulus of more conventional materials when below the glass transition point (T_g), yet demonstrate low modulus and the memory capabilities when heated. Shape memory materials are similar to traditional fiber-reinforced composites except for the use of shape memory polymer resins. The unique properties of the resin enable the fiber-reinforced SMP materials to achieve high packaging strains without damage. The ability to accommodate high packaging strains allows a structure to be packaged compactly for launch and subsequently deployed to the as-cured shape by releasing the stored strain through application of heat. The deployment temperature is adjustable through changes in the resin formulation.

A. Shape Memory Characteristics

The unique properties of the shape memory resin enables SMP materials to achieve high packaging strains without damage. Strains are induced by elevating the temperature of the SMP material and then applying a mechanical force. The shape memory characteristics enable the high packaging strains to be “frozen” into the SMP by cooling. Deployment (i.e., shape recovery) is affected by elevating the temperature. At normal operating temperatures, the performance of SMP materials follows classical composite laminate theory. At higher temperatures, SMPs exhibit dramatically reduced stiffnesses due to significant matrix softening of the resin as shown in Fig. 2. The localized heat application allows for unique stress/strain relief versus normal composites. Addressing the mechanics of the “soft-resin” will enable the SMP materials to provide repeatable stowage and deployment performance without damage and/or performance changes.

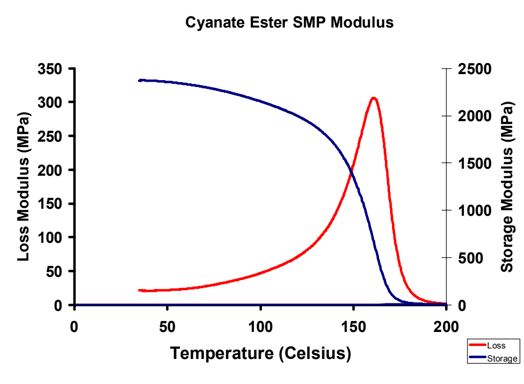

Fig. 2: Modulus Curves for Baseline Cyanate Ester SMP, $T_g = 160^oC$

Mirrors can be formed by substituting SMP materials for the usual resin matrix in the composite. The polymer resin selected for these mirror fabrication tests is a cyanate ester, modified for shape memory properties by Cornerstone Research Group, Inc. (CRG). Other than shape memory characteristics, resin properties appear to duplicate conventional cyanate esters. Outgassing tests showed a measured TML of only 0.17% for the CRG material, indicating complete crosslinking of polymer chains characteristic of complete cure. While this material is still in development, the test data and similarity to existing resins used in composite structures suggest it can be qualified for space applications, and further tuned to requirements of deployable optics. Mechanical strength in a reinforced composite matrix is consistent with self-supporting membrane optics. Durability in the space environment (radiation, atomic oxygen) is expected based on similarity to current cyanate ester formulations used in space.

Repeated cycles show full strain recovery to "memory" shape after repeated deformation and relaxation. Quantitative DMA testing of the baseline SMP confirmed complete strain recovery when repeatedly elongated to 10% (Fig. 3), thus demonstrating true shape memory property. The apparent small residual strain shown in cycles 4-6 was due to the mounting apparatus seating into the specimen. A 100mm graphite fiber reinforced sample exhibited deployed positional repeatability of 0.1mm after more than 10 bend and deploy cycles of 180 degrees. Further measurements are planned to confirm the repeatability for various reinforcing structures and formulations, and measurement of creep and environmental stability in vacuum.

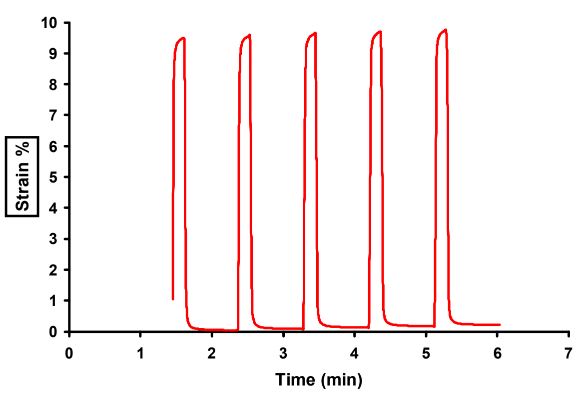

Fig. 3: Shape Memory Confirmed by Full Strain Recovery from Repeated 10% Deformation

B. Shape Memory Advantages

Shape memory composites provide notable advantages over other composite optics in deployed applications. A conventional composite requires significant stored energy for the stowing and deployment, and a complex mechanism for slowly releasing the stored energy in a controlled fashion. The optical surfaces must be protected during launch. A shape memory optical structure can be stowed, and structurally rigidized in a configuration that protects optical surfaces from abrasion or damage. Mechanical hinges linking segments are not required, reducing mass, complexity, backlash, and lubricant contamination associated with motors, bearings and hinges. A monolithic deployable mirror will not have the defects associated with adjoining mirror segment edges. Composite replica optics share the low cost replication, however shape memory polymer optics have a further possibility of custom shape tuning

C. Replication Schemes

Two replication schemes are currently being investigated. The first produces an electroformed metal surface on an optical mandrel, and the composite substrate is applied to the back surface of the electroformed metal layer. The second method replicates the optical surface by placing the composite on the mandrel. The replicated composite is removed from the mandrel and becomes the substrate for the electroplated metal layer. The performance of the mirror will depend very much on the quality and performance of the replicated composite facesheets and electroplated metal surface. High replication accuracy requires a resin-rich composite surface, while thermal stability is improved by a fiber-rich composite. Fiber print-through can become an issue in fiber-rich composites, however this problem is much reduced by having a thicker electroformed metal reflecting surface layer. Compactness of stow or accuracy of the deployment would be sacrificed due to microyield of the thicker nickel. Ref. [5].

V. RESEARCH APPROACH

The current work builds on existing high-quality optical replica electroplating capability at Northwestern University, the proprietary SMP materials developed by CRG, and development of light-weight precision optics at Ball. Although there is an existing basis for the technology, the development of shape changing composite structures is in its infancy. Examples are the lack of structural models for describing composites during soft resin states and while deformed and locked in a stowed configuration.

A. Modeling

A model was developed in parallel with the testing effort. The main goal was to use the material, thermal and structural performance models to predict deployment deformations given a certain design. Characterization and definition of properties, both material and thermal, of process procedure and control, and of geometry of the mirror was the expected outcome of the modeling effort.

The current model is a simple Excel based model that incorporates thermal, material and structural properties. Formulas were taken from Roark [6], Sarafin [7] and Timoshenko and Goodier [8]. Material and thermal properties are included as defined by experimentation. Geometric properties considered both flat and spherically shaped mirrors. Each layer is assumed to be homogenous but is modeled separately from its neighbor. This enables the user to "engineer" the needed materials and create preferential shaping. For instance, by matching CTE differences in particular layers, a smaller curvature may be realized for stowage.

This model was run for an early sample made of Styrene SMP with 3D Weave Carbon. Simulation of the deflections ("roll-up") of convex samples in the oven resulted in modeled data within 50% of the experimental data. Both temperature (110 degrees C as used in the experiment) and additional force due to the roll up were incorporated. The change in "length", or in this case, diameter, of flat samples due to temperature change was within 20% of experimental data.

Comparison of model results and experimental results show promise for using the model to help define hardware parameters and provide information for future sample preparation. Unfortunately, this simplified model has a low confidence level. Therefore, a more rigorous model, using finite element and thermal models will be developed before moving on to the next steps. The new models will include comparison with strain measurements made on samples as well as the ability to scale to different mirror sizes.

Future work includes the use of a formal Integrated End-to End Modeling (IM) environment being developed at Ball. The Ball IM is a Simulink / MATLAB based environment that provides an end to end system engineering tool. This modeling scheme, under development for 7 years, represents the state-of-the-art integration capability for coupled models. It permits the user to perform both time simulations and analytical work in the spatial and temporal frequency domains. The individual discipline models in structural dynamics, optics, controls, signal processing, detector physics and disturbance modeling are seamlessly integrated into one cohesive model to efficiently support system-level trades and analysis. Discipline experts retain their traditional roles but this approach also uses parallel path of rapid subsystem modeling and integrated system modeling. Integrated modeling allows for combined interaction of subsystems while monitoring system performance metrics.

The above mathematical models can be easily added to an integrated end-to-end model being developed under other applications. The IM can include theoretical models for items such as the affect of material microyield [5] on the mirror wave front error. From here, we can determine which material properties need to be adjusted for the desired stowed geometry.

B. Test Item Fabrication

We have begun by matching requirements for a typical composite reflector to existing materials with known properties and using a demonstrated mirror electroforming process. Control of interface stresses between the nickel and composite has been the major focus of the initial tests because of the criticality to success, and the novelty of the approach. We have defined the process requirements for the nickel, considering mandrel separation, adhesion, roughness, thickness, and stress control, according to the current best practice optical plating processes. Composite goals include definition of requirements of the composite substrates that currently limit application of composite optics. This includes dimensional stability during cure, low thermal expansion coefficient, high specific stiffness, minimal fiber reinforcement print-through, low or no micro-cracking, low outgassing and low moisture uptake, compatible processibility and processing time, evaluation of alternate reinforcement materials and reinforcement architectures, fibers and fiber combinations, nano-reinforcements.

C. Results

Critical to validating the concept was the need to verify adhesion of disparate materials as composite and nickel. Surface accuracy, smoothness, and material outgassing goals were accomplished in part. Investigation is continuing on nanofiber and fabric reinforced materials, and symmetric layers to isolate the optical surface from the reinforcing layers.

1) *Shape Memory properties:* Repeated stow-deploy temperature cycle tests showed the composite was not damaged by repeated rolling up the laminated mirrors to 50mm radius. Specially shaped test samples demonstrated deployment repeatability to about one part in 10,000, but flat and spherical pieces do not yet achieve this value.

2) Lamination Integrity: Adhesion of composite to nickel has been accomplished through physical roughening of the nickel. Temperature (-18C to +110C) and deployment (100mm radius bend) cycles demonstrated adequate adhesion through multiple cycles with bend radii of less than 30mm demonstrated in Fig. 4. Compliance of the soft resin is apparently sufficient to reduce interface shear loads within adhesion limits during deformation in the soft state, but it is not clear that additional thermal or mechanical loads will not cause delamination.

3) *Replicated low scatter surfaces*: Mandrel roughness was reproduced with a 2nm RMS replica surface roughness. The laminated nickel optical surface does not permanently deform or wrinkle during roll-up of the optic as long as there is no delamination. Print through is still noticeable, but was reduced through the common practice using layers of high resin content composite adjacent to the nickel surface.

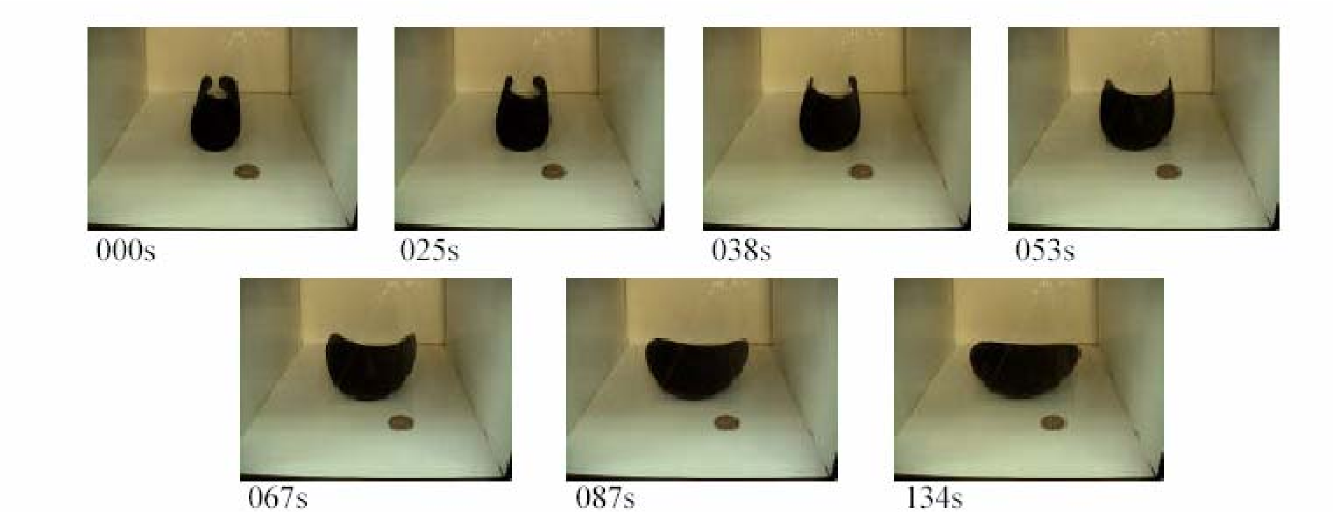

Fig. 4. Mirror substrate deployment sequence in a 110 degree C oven

VI. Future Directions

We plan to manufacture and test additional samples of composite materials suitable for optics, Stability of both the stow and deployed configurations, particularly under vacuum environmental conditions, needs to be investigated further. Scaling the results of these small samples to predict behavior of 5m and larger structures will be necessary to fully utilize the deployable properties. Improved optical figure control allows wider use of the technology in shorter wavelength bands, but requires much more precise process controls and modeling prediction capability. Current deployment repeatability data suggest microwave reflectors spanning over a meter will maintain sufficient accuracy for aperture limited resolution typical of current composite reflectors even after stow and deployment. Strawman requirements will be the focus of future development.

VII. Conclusion

Shape memory materials are becoming available and better understood for space structures have applicability to large deployable optics. New mission concepts involving novel stow and deployment schemes may be possible given increased design latitude. Shape memory materials incorporated replication processes have the potential for further exploitation to expand the range of applications for composite optics.

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